known in carbonaceous chondrites, but not in ordinary chondrites. It is thus very surprising that Zolensky *et al.* found coarsely crystalline halite (NaCl), not ordinarily known as an igneous or metamorphic mineral, inside a metamorphosed ordinary chondrite, Monahans, which fell on 22 March 1998 in Monahans, Texas. Evidence that the halite was deposited from aqueous solution is provided by the presence of tiny (5 μm long) inclusions of brine. The meteorite was recovered rapidly after its fall and examined under clean-laboratory conditions, ensuring that the halite and its fluid inclusions are not terrestrial contaminants.

Zolensky *et al.* recognize two alternative explanations for their unique observation. Water-deposited minerals may actually be common in ordinary chondrites but are usually dissolved away before examination. Alternatively, Monahans may be an exceptional meteorite, bearing minerals deposited by solutions from an exotic source, such as a cometary impact on the surface of the parent body. In the former case, the authors are rewarded for their prompt action and careful study; in the latter case, they are lucky that a one-of-a-kind meteorite happened to fall in Texas, where their laboratories are located.

Even when actual samples of nebular water are not available, its influence on the formation of planetary materials may leave recognizable features in the rocks. Interaction between nebular gas and condensed phases may be revealed by variations in abundances of isotopes of the light elements. Isotopic exchange between nebular water vapor and the molten precursors of chondrules and refractory inclusions leaves an isotopic imprint on these meteoritic components. Quantitative interpretation of the exchange processes requires knowledge of the isotopic composition of the water vapor in the solar nebula, which can be estimated from the isotopic compositions of clay minerals and carbonates formed by aqueous reactions within parent bodies (*4*). A direct sampling of the solar wind is planned for the Genesis spacecraft mission (*5*). Isotopic analysis of the sun or comets by remote spectroscopy is not sufficiently accurate for this purpose. The brine inclusions discovered by Zolensky *et al.* provide the first opportunity for the direct isotopic analysis of a meteoritic water sample, but such an analysis is difficult because of the small size of the inclusions. Each inclusion contains on the order of a picomole of water, which is beyond the capability of existing high-precision mass spectrometers by about a factor of a thousand.

Brearley finds that the matrix olivine of the famous carbonaceous chondrite Allende contains nanometer-sized grains of a sulfide and of poorly graphitized carbon, which could not have survived a high-temperature crystallization of the olivine. This is taken to support the proposal of Krot *et al.* (*6*) that iron-rich olivine (in Allende and elsewhere) was produced in a two-stage process consisting of hydration within the parent body to form iron-bearing clay minerals, followed by thermal dehydration to produce iron-rich olivine. As noted by Brearley, a stumbling block for the hydration-dehydration hypothesis is the absence of the expected signature in the oxygen isotopic composition of the Allende matrix. On the three-isotope plot that records the high-temperature interaction between nebular gas and solid minerals, the matrix composition does not show heavy-isotope enrichment, which is readily observed in other meteoritic components with unambiguous evidence for low-temperature processes.

These two reports provide an interesting contrast. Brearley, dealing with a carbonaceous chondrite, infers the transient presence of water from the absence of high-temperature reactions with trace phases. Zolensky *et al.* have actual samples of meteoritic water, found in a meteorite where it is not expected. It is analogous to the contrast between the Cheshire Cat and Goldilocks. By following a well-marked trail of water long gone and fortuitously finding a sample of primordial water, the studies fill in some of the gaps in the story of aqueous alteration of meteorite parent bodies.

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PERSPECTIVES: GEOPHYSICS

A Seismic Look Under the Continents

Karen M. Fischer and Rob D. van der Hilst

Even a casual glance at topographical and geological maps reveals striking differences between continents and oceans. The continents stand on average 4.6 km higher than the ocean floor. And at up to 4 billion years in age, their crusts are much older than the oceanic crust, which is at maximum 200 million years old (Ma). Seismic studies have shown that these differences continue below Earth's surface. Continental crust is thicker and more chemically buoyant. Also, the lithosphere—the rigid outer layer of Earth including the crust and part of the upper mantle that sustains plate tectonics—reaches depths of no more than 100 to 125 km under the oceans, whereas lithospheric "keels" extend to depths of 250 km or more beneath most stable continental interiors. Seismic, gravity, and geochemical data have shown that these continental keels are both cool and chemically buoyant (*1*, *2*) and that they have been mechanically coupled to the overlying cratonic (*3*) crust for billions of years (*4*), keel and crust moving together in the plate tectonic cycle. However, many aspects of keel composition, formation, and subsequent modification by flow in the surrounding mantle and by continental collision and rifting have remained enigmatic (*5*). Extensive seismic array studies are now shedding new light on continental keels.

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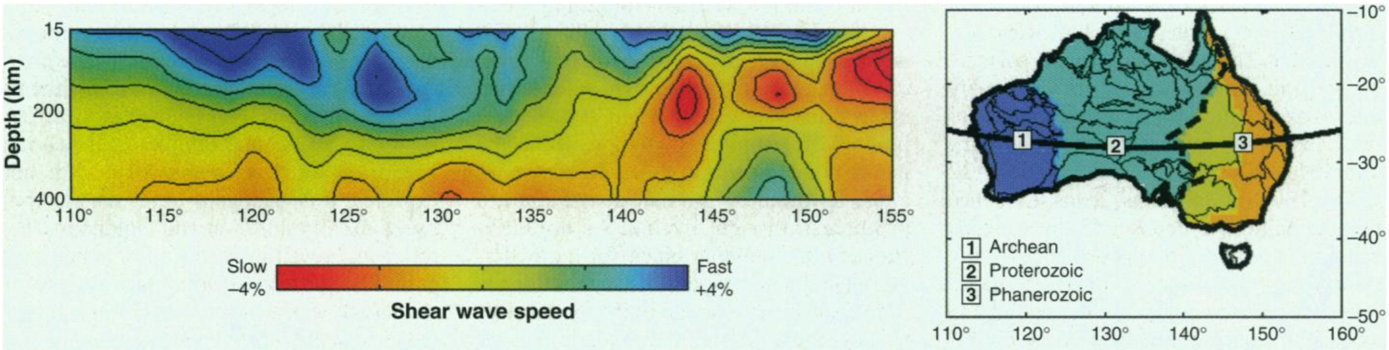
Restricted by sparse data, studies of the continental mantle long relied on broad correlations between geological and geophysical data sets, which assumed that processes underlying keel formation and evolution were uniform from region to region. In the last decade, however, higher resolution analyses of data from dense arrays of broadband seismometers have demonstrated that continents are extremely complex assemblages and that the relations between the composition and seismic signature of the continental keels and their age and geodynamic history are more variable than previously assumed.

The speed at which seismic waves travel through different parts of the mantle is indicative of the properties of local materials. Global models of mantle wave speeds have suggested that keels beneath stable cratons reach depths of 400 km or more (*6*). But recent seismic imaging of cratonic regions in southern Africa (*7*), Tanzania (*8*), Australia (*9*), North America (*10*), and Brazil (*11*) has shown that the

K. M. Fischer is in the Department of Geological Sciences, Brown University, Providence, RI 02912, USA. E-mail: karen_fischer@brown.edu. R. D. van der Hilst is in the Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. E-mail: hilst@mit.edu



Continental keels reveal their secrets. (Right) Seismic wave speed anomalies in the mantle beneath Australia averaged within crustal age domains; up to about 200 km in depth, wave speeds systematically increase with crustal age. **(Left)** An upper mantle profile of wave speed anomalies beneath Australia (see map for profile location) further illustrates the dramatic variation in lithospheric mantle structure across the continent. The Phanerozoic (<570 Ma) domains in the east are characterized by a thin lithosphere, whereas in the central Proterozoic (570 to 2500 Ma) and western Archean (>2500 Ma) parts of the continent, the keel extends 200- to 250-km depth.

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fast wave speeds characteristic of lithospheric mantle are generally concentrated above 250 km (see the figure), although in a few regions they reach depths of 300 km or even 350 km. The data indicate that keels are largely confined to Earth's upper mantle (at depths of less than 410 km) and are not anchored in the transition zone (from 410 to 660 km) to the lower mantle.

This conclusion is corroborated by studies of upper mantle discontinuities. The mineralogical phase boundary between olivine and wadsleyite creates a discontinuous jump in seismic wave speed at average mantle depths of about 410 km, but shallower in colder regions. High-resolution studies of discontinuity depths across keel margins in the eastern and western United States and in Tanzania (*12*) imply that in these regions the cold keels do not reach depths of 410 km and that, at least today, cold vertical downwelling beneath them is insignificant.

Anisotropic variations in wave speed likely reflect strain-induced alignment of olivine crystals in the mantle and thus provide a measure for deformation processes. The presence of azimuthal anisotropy in the mantle to depths of about 200 km just outside the keel in eastern North America provides further evidence that mechanical decoupling between the keel and the surrounding mantle occurs well above the transition zone (*13*). However, tomographic images of the upper mantle beneath Brazil have been interpreted as showing an upwelling plume that moves with the South American plate, implying that surface plate motion and upper mantle flow in this region are coherent to much larger depths (*11*).

The seismic array studies also show that the margins of continental keels and cratonic crust are not coincident everywhere and that lithospheric thickness may vary substantially even within domains of similar geological age or crustal evolution. These results suggest that either keels may form with complex morphologies or that they have been extensively altered by continental collisions and rifting in certain regions, but not in others. Beneath the Tanzania craton, the keel appears to be largely intact despite rifting and plume activity around its margins during the past 30 Ma (*8*). In contrast, broad areas of former cratonic crust, or what used to be cratonic crust, now lie above low wave speed, nonkeel mantle in the western and northeastern United States (*10, 14*), southwestern Fennoscandia, and eastern China (*5*). Elsewhere, keels seem to extend beyond the surface craton, for example, in eastern Australia (*9*).

Anisotropies in continental mantle wave speeds are also more diverse and complex than suggested by earlier, sparser data sets (*7, 15*). This may be a result of different thermal and tectonic histories and keel morphologies. Neither lithospheric strain correlated with surface geology nor simple predictions of sublithospheric flow alone can explain these data on a global basis. Furthermore, substantial heat flow variations can occur within provinces of a single geological age, challenging the validity of universal heat flow–age relations (*16*). Global generalizations regarding keel properties and processes should thus be considered with considerable caution.

Near horizontal, sometimes anisotropic, layered structures have been isolated within keels to depths of 250 km (*7, 17*), including a striking example of a deep mantle discontinuity that appears to be the continuation of a shallowly dipping ancient subducted slab imaged in seismic reflection profiling (*17*). This result provides the strongest evidence to date that keel formation involved stacking of subducting lithosphere during collisions between continents or island arcs (or both).

These higher resolution studies reveal continental keels to be upper mantle features that contain great variability within and between cratonic regions. To further understand the genesis and evolution of continents, concerted research efforts, such as USArray (*18*), are required. These must involve geophysical, geological, and geochemical mapping over a wide range of length scales, with particular emphasis on cross-disciplinary analyses that bridge the gap between conventional mantle imaging and high-resolution mapping of crustal structures.

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